AD NUMBER
AD890720
NEW LIMITATION CHANGE
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OPERATIONS RESEARCH, Inc.

SILVER SPRING, MARYLAND

THE ASW CLASSIFICATION PROBLEM
IN A MULTICONTACT ENVIRONMENT—
A QUEUING APPROACH

by
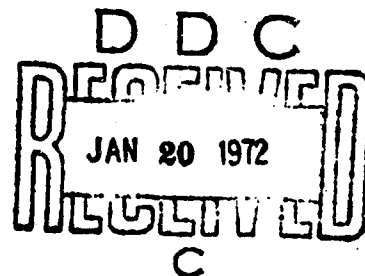
P. M. Tullier and D. W. Walter

20 December 1971

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DOCUMENT CONTROL DATA · R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Operations Research, Inc.	Unclassified
	2b. GROUP N/A

3. REPORT TITLE

THE ASW CLASSIFICATION PROBLEM IN A MULTICONTACT ENVIRONMENT—A QUEUING APPROACH

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Interim Report

5. AUTHOR(S) (Last name, first name, initial)
Tullier, Pierre M. and Walter, Donald W.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
20 December 1971	25	1

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
N00014-71-C-0408	
b. PROJECT NO. RF 018-96-01	TM 138-71
c. NR 364-047	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
- - -	Naval Analysis Programs (Code 462) Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT   The passive classification process aboard a submarine is studied. In particular the operations of the sonars in a multicontact environment are treated as a time-shared processing system. The processors are the passive sonars and the customers are the sonar contacts. This interim report gives the rationale for describing the system in this manner. The queuing system equations are not yet formulated. General measures of effectiveness are presented which can be obtained through the queuing approach.

DD FORM 1473 1 JAN 64

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
ASW						
Classification						
Queuing						
Time-shared system						

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SUMMARY

This memorandum reports on the progress ot work done under ONR Contract N00014-71-C-0408, "Dynamic ASW Formulation." System components are analyzed and a method of approach is outlined.

OBJECTIVE

The objective of this research effort is to develop methodology for the dynamic (time-dependent) aspects of the onboard ASW operations of an SSN submarine. A fundamental characteristic of ASW operations onboard an SSN that is of interest here is the requirement for overlapping observations of several targets. This can lead to congestion at various points in the system and subsequently to time delays in the processing of contacts. Since server/customer relationships appear in the ASW system, queuing theory is considered as a method for determining the effects of congestion. In general the servers are the passive sonars and the customers are the contacts. The service performed is the detection, classification, and disposition of contacts.

SCOPE

There are several types of SSN submarines and several scenarios for their employment in antisubmarine warfare. For purposes of analytical development, the SSN 637 class submarine on patrol in an open ocean barrier is used in this report as a frame of reference. The methodology developed here should be applicable to other submarines in other missions as well. The SSN 637 carries the BQS-6, BQR-7, BQQ-3, sonar system, and the Mk 113 fire control system in its equipment suite. For the purpose of this study the submarine is assumed to be operating independently in a passive mode. The threat is assumed to be a first or second generation Soviet submarine.

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The ASW system is described in terms of four subsystems—detection, classification, localization, and attack. The localization subsystem is subdivided into localization-for-information and localization-for-attack. The information flows and decision sequences are studied for the subsystems. The detection/classification/localization-for-information system appears to contain most of the congestion and is thus the most likely place to apply queuing theory. The localization-for-attack and attack systems are entered when a target has been confidently classified as hostile. If the decision is made to attack, almost all activity is focused on the target. This is the goal of the entire mission. In a situation of such single-minded attention, queuing theory is not particularly applicable unless there are many targets to attack; and even if there are several targets to attack, it is more a question of tactics than of analysis of waiting times. Localization-for-attack and the subsequent attack have been modeled extensively from other, more appropriate points of view. For these reasons the analysis is directed to the detection/classification operations.

FINDINGS

Queuing situations discovered in the detection/classification system are as follows: (a) no classification queue, (b) preliminarily classified queue, (c) Mk 113 fire control queue, (d) control room plot queue, (e) known range, speed, and course queue, (f) localize-for-information queue, and (g) dormant queue. These queues and their interrelationships are described.

Preliminary measures of effectiveness are presented. These include probabilistic and expected value measures. The measures are conditioned on the congestion in the system. This is expressed as a weighted sum of the priority of each class of targets and the number of targets in that class.

The queuing theory approach that appears the most promising is not the usual approach. In this paper the detection/classification problem is viewed as a time-shared processor problem. The sonars are considered to share their time between contacts of varying priorities. The development of this approach is begun in this memorandum. The classification process is described in detail at the outset, as a means of understanding the processing time for a contact, and the nature of information presented to the sonar operator is analyzed to lay the ground work for the queuing model.

CONCLUSION

This technical memorandum describes the ASW mission, its subsystems, and their information flows. It analyzes certain problems in the classification of contacts with a view toward applying queuing theory. It demonstrates the application of a "time-shared system" approach to the sonar/contact processing system. Future work will investigate the mathematics required to implement this approach.

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I. INTRODUCTION

This report begins a research investigation of the dynamic aspects of the ASW operations aboard an SSN 637 class submarine. This mission often requires overlapping observations of several targets, which may lead to congestion at various points in the system. Queuing theory is considered as a possible approach to modeling the congestion problem. The results of ORI's investigation will include recommendations on the applicability of queuing theory, taking into account the assumptions required by the theory and their relation to the real world, the data required to implement a queuing model, and the possibilities for a mathematical solution. Existing simulations of this problem will be studied and comparisons drawn with any queuing models discovered. The queuing theory approach is being investigated because server/customer relationships appear in the ASW system. In general the servers are the passive sonars and the customers are the contacts. The service that is performed is the detection, classification, and disposition of the contact. In a multicontact environment time can play a critical role. Queuing models can give measures of effectiveness that contain the time factor. ´

To obtain these measures for a specific system, care must be taken in the definition of the system components—customers, servers, and service discipline. Often these components are easy to discover and define, especially in systems resembling classical waiting lines, such as supermarket checkout stands, banks, and repair facilities. However, in situations that may contain subtly disguised queuing systems, the "customer" may not be obvious. Similarly, the kind and number of "servers" may be hidden behind the veneer of a deceptively simple formulation. And the definition of service discipline, which is the manner in which customers are served, may change like a chameleon with the angle from which it is viewed. The service discipline can be of several forms, such as first-come first-served, preemptive priorities (service

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is interrupted for a higher priority customer), nonpreemptive priorities, time-dependent priorities and round-robin serving (as in a computer time-sharing system). These service disciplines can be combined in many ways to yield the type required by the system under consideration. In addition, of course, a new discipline may arise for a new application of the theory.

The basic data required to implement the queuing theory approach to a congestion system are the arrival rate(s) of the customers and the service rate(s) of the server(s). These rates are treated in terms of probability distributions for the time between successive arrivals and for the service time of each arrival. These distributions may be difficult to obtain, depending on the data. They may also be difficult to handle analytically, depending on the complexity of the system. If the entire system is composed of several smaller, interdependent systems, the task becomes more difficult. If the true interrelationships can be discovered, queuing theory can give results under certain conditions. If these conditions are not met in practice, they can be assumed and the results interpreted in light of the assumptions.

Special situations in queuing systems, such as balking (refusing to enter the waiting line) and reneging (leaving the waiting line before being served) have been analyzed in the existing body of queuing literature. Since losing a customer either through balking or reneging is not desired in most applications, some models include methods for designing service facilities and disciplines that minimize balking and reneging. In certain applications, however, the balking and reneging are not even indirectly under the control of the server. Consideration of these factors adds to the complications introduced by complex service disciplines. For the reader who is unfamiliar with queuing theory, Appendix A provides definitions of the terms used throughout this report.

II. GENERAL SYSTEM DESCRIPTION

SCENARIO

The scenario for this analysis is assumed to be an open barrier where-in an SSN 637 class attack nuclear submarine has an assigned mission to investigate all contacts obtained and to attack and destroy all hostile sub-marines. The SSN 637 is operating independently and is assumed to be the only friendly submarine in the area. The SSN will remain in the passive detection mode of operation and will not use active sonar even immediately prior to weapon delivery

The specifics of this scenario are intended only as a base from which methodology can be developed. Such things as class of submarine and its equipment suite are not fundamental to the analysis that follows.

System Parameters

The contacts arriving in the area of concern do so randomly in terms of both time between arrivals and true bearing of initial detection. The possibility of contacts proceeding in company with like and/or unlike contacts is considered feasible and is addressed.

The environmental conditions are assumed to vary across the spectrum with regard to elements such as range of initial detection and contact retention capability. With regard to technological advantages of the SSN system versus arriving contacts, it is assumed that SSN 637 will encounter adversaries of various degrees of sophistication. This allows for some contacts to be no match for the system and for some relative stand-offs.

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Subsystems

The vital subsystems onboard the SSN will perform up to specifications with regard to functional capabilities, reliability, maintainability, and availability. Operator achievement will be that expected of a well-trained, experienced crew; also, it will be assumed that decision-making and priority selection will be that of a well-trained organization.

The subsystems of particular importance to the mission include the BQS 6 (passive), BQR 7, and BQQ 3 sonars, and the Mk 113 fire control system. The personnel of particular importance include those engaged in sonar control, ship control, fire control, sonar plotting, and weapon launching operations. It is assumed that ship control will be completely responsive to demand in terms of course, speed, and depth and will not degrade the system performance except as predictable by a given set of requirements (e.g., exceeding cavitation speed for a given depth).

SYSTEM DESCRIPTION

An SSN 637 class submarine on an ASW mission must proceed through four stages. These are shown in schematic form in Figure 2.1. The first stage is detection. This normally involves continuous searching of the ocean with passive sonar. When a potential target is detected the next stage is entered—classification. This stage includes the operations necessary to identify the contact. The time spent in this stage may vary greatly, depending on the target characteristics and system parameters. Upon classification the next stage is entered—localization. The overlap in the diagram shows that classification may still be taking place during localization. This stage represents the operations that will give an accurate picture of the target's sound signature, range, course and speed. As these data are obtained, and if the mission requires it, the submarine moves into the last stage—attack. In this stage the submarine obtains the best firing position and deploys its weapons.

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┌──────────────┐    ┌──────────────┐  ┌──────────────┐   ┌──────────────┐
│              │    │  CLASSIFI-   │  │              │   │              │
│  DETECTION   │────│   CATION     │  │ LOCALIZATION │   │   ATTACK     │
│              │    │              │  │              │   │              │
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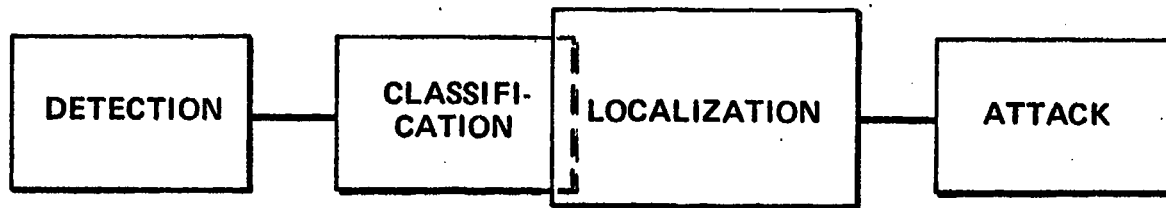
FIGURE 2.1. SCHEMATIC FLOW DIAGRAM OF SSN 637 ASW MISSION

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Essential elements in each stage are the passive sonars (BQR-7 and BQS-6). Through the description of the stages it will become obvious that these sonars are required to perform several concurrent tasks. Thus a major characteristic of the system is the requirement that the sonars divide their time between competing tasks. In other words the sonars must be time-shared. An accurate description of this characteristic is fundamental to building a successful queuing model. The model must also reflect the fact that the sonars are not identical processors.

Each of the blocks in Figure 2.1 represents an information flow and an associated sequence of decisions. The paragraphs below will describe this substructure as it is shown in Figure 2.2 (foldout at end of memorandum).

Detection

A sonar contact is usually made in either of two ways:

a. The sonar operator can hear the sound energy as he manually sweeps the sonar

b. A line may appear on the bearing time recorder (BTR) which represents the energy received by the omnidirectional section of the BQS-6 sonar.

The range at which detection is made depends upon many factors, such as acoustic frequency, target source level, sound velocity profile, operating depths, and sea state. Because of these factors it is difficult to say when a particular target is "available" for detection. However, a bad search pattern would be one that allowed a target to become "available" and then depart without being noticed.

Classification

When the sonar operator detects a contact he reports it to the conning officer as a "noise level" if he cannot preliminarily classify it. When a preliminary classification is made the conning officer is notified. At this point the sonar operator may try to compute target range using the passive bottom-bounce method. If this can be done, the conning officer is notified of the results. To accurately classify a contact the signal to noise ratio of its sound signature must be above some minimum level. Additional information such as target range and speed can effect the classification. The actions required to obtain this information are at the discretion of the conning officer. His decisions are influenced by the number and types of other current contacts.

Most of the data given to the conning officer come from the passive sonars. If more than one contact is being investigated for range, course, speed, bearing rate, and frequency spectrum the conning officer must make some priority decisions. Which contact the sonar listens to and for how long is an important question. As information is generated on a target, confidence in the accuracy of the classification increases. When a final classification is made that the contact is not hostile, it is set aside and inspected periodically. If

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the contact is finally classified as hostile, an action decision (shoot, or avoid) must be made. This decision depends upon such things as the type of mission and the type of target.

Localization

There are two types of localization: localization-for-information, and localization-for-attack. The first type consists of getting closer to a contact to learn more about it. These maneuvers aid greatly in determining the range, course speed, and sound signature of the contact. The second type, localization-for-attack, is concerned with obtaining the most accurate target position possible. Since this stage is preparatory to attacking the target, most activity is concentrated here. Thus while keeping track of the other contacts held and continuing to search for new contacts, the SSN will concentrate more and more services on the contact being localized as the range decreases. The fire control solution being generated in the Mk 113 should improve with time, particularly as own ship changes course and/or speed to develop a true solution and if and when a propeller shaft turn count is obtained allowing a reasonably accurate estimate of target speed.

Attack

In the attack phase the submarine is maneuvered into the best firing position and the weapon is launched. Almost all effort is focused on the target. One of the passive sonars may be searching the area for other hostile targets during this phase (usually the BQR-7).

Equipment

The BQS-6 can operate in either the active or passive mode. As stated above this analysis considers only the passive mode of operation. The operating characteristics of this sonar and other equipment can be found in the Ship Information Books for the SSN 637. [1] This data is not repeated here in order to keep the report unclassified. The BQR-7 operates strictly in the passive mode. It has different characteristics than the BQS-6 and these differences influence the operational use of the sonars. A queuing model must take these differences into account. The BQQ-3 is a display device which aids in the classification of sonar contacts. Its use must also be considered in any queuing model. These equipments are not specifically modeled in this report since the methodology must allow for general types of equipment. If a useable mathematical model is developed specific equipment capabilities will be included.

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[1] Naval Ship Systems Command, General Information (U), USS Sturgeon SS(N) 637, Ship Information Book, Volume 1, NAVSHIPS 0905-019-0010, July 1967, CONFIDENTIAL.

- Naval Ship Systems Command, Tactical Facilities (U), USS Sturgeon SS(N) 637, Ship Information Book, Volume 2, NAVSHIPS 0905-019-0050, July 1967, CONFIDENTIAL.

III. QUEUING SITUATIONS IN THE SSN 637 ASW MISSION

This section describes queuing systems in the ASW system. The descriptions are not mathematical in nature; they are intended to lay the foundation for a mathematical analysis in the final report. The section starts with a discussion of the overall system and then proceeds through the various subsystems.

OVERALL SYSTEM QUEUE

When looked at from a distance, the submarine appears to be a black box that inspects sound contacts, processes them, and, on completion of processing, ignores, attacks, or avoids the object making the sound. This box has two primary sensors. The sensors are the passive sonars and they cannot concentrate on all contacts at once. Situations arise when a contact must wait its turn to be investigated. Thus, we have the beginnings of a queuing system. The passive sonars are the "servers", and the sound contacts are the "customers." The service discipline appears to be of the time-sharing type, since the customers are looked at many times, sharing the attentions of the sonar with other contacts, before their service is complete.

Because certain contacts are more important than others, some sort of priority scheme must be added to the service discipline. This is discussed in Section V. The service to be provided is classification. Upon detection of a contact a sequence of events begins onboard the SSN 637. The ultimate result is some kind of classification decision. The process of classification, its structure and data requirements, are discussed in Section V. The subprocesses of the classification process are described in the remainder of this section.

SUBSYSTEM QUEUES

Figure 2.2 shows various congestion points in the information flow and decision sequences that occur in ASW operations. These subsystems queues occur at points where contacts are waiting for sonar attention; other queuing situations occur which do not have the sonars as servers. The different subsystem queues are listed here for reference:

- Subsystem sonar queues
    - No classification queue
    - Preliminarily classified queue
    - Determine range/speed, and course queue (Mk 113 fire control system)
    - Determine range/speed, and course queue (plotters in control room)
    - "Known" range/speed, and course queue
    - Localize for information queue
    - Dormant queue (contacts classified as nonhostile or false)
- Subsystem queues without sonar servers
    - Mk 113 fire control system queue
    - Control room plots queue
    - Conning officer decision queue.

Queues With Sonar Servers

No Classification. These contacts have been heard as noise levels, but the information required to make a preliminary classification is missing. The contacts are noted and inspected later. If the sonar operator can make a preliminary classification, the contact moves to the next queue in Figure 2.2, "Preliminarily Classified." It is possible that a contact in this queue will be lost; that is, on the next look the contact will not be heard. This is a form of reneging.

Preliminarily Classified. These contacts have some preliminary classification given by the sonar operator. He has attempted a passive bottom-bounce ranging and that information is passed on to the conning officer. The contact stays in this queue until the conning officer decides to get more accurate range and speed information via the Mk 113 fire control system or the plots. The contact is investigated periodically, and eventually is either lost or passed on to the next queue—"Determine Range/Speed, and Course."

Determine Range/Speed, and Course. Range, speed, and course estimates of a contact can be obtained through either the Mk 113 fire control system or the manual efforts of the plotters in the control room. Each of these methods requires periodic input from the passive sonars. When an estimate of the range, speed and course of the contact is obtained, the contact passes to the next system—either "Localize-for-Information," or "Wait" with range, speed and course "known".

Known Range/Speed, and Course. Contacts in this system are periodically investigated and reports made to the conning officer. Eventually these contacts are lost, identified without localizing for information, or localized for information.

Localize-for-Information. This queue contains contacts that merit more accurate range, speed, and course information. A revised estimate of range, speed, and course may be obtained and no further action ordered. In this case the contact again enters the known range, speed, and course queue. Another possibility is that the conning officer can make a final classification decision. If he does, the contact either goes to the dormant queue, meaning it has been confidently classified as not hostile, or the conning officer makes a decision to attack or not, depending on the submarine's mission.

Dormant. These contacts have been classified with a very high probability as nonhostile or false. They are investigated periodically, just in case they are not, but generally they leave the system as they move out of range.

Queues Without Sonar Servers

Mk 113 Fire Control System. This system consists of two parallel problem analyzers. Each analyzer can solve the range, speed, and course problem for a contact. The conning officer decides which contacts should be processed, and if he needs information on more than two at about the same time, a waiting-line develops for the Mk 113. This situation might be looked at as a straightforward queuing problem—put one contact in, process it, and go on to the next. However, the solution depends entirely on sonar inputs. Thus the service time of the Mk 113 depends upon the number of contacts in the total system. This may not be a problem if the input to the Mk 113 is treated with high priority, so that inputs arrive from the sonar at a rate independent of the number of contacts in the total system. Priorities for the fire control system are set by the conning officer as he makes decisions as to which contact the Mk 113 processes. Further, it is preemptive priority system, since the conning officer may decide to stop processing on one contact to process another. If a preemption occurs the partial solution on the discontinued contact is lost completely. Thus, ultimately, the Mk 113 fire control system is a preemptive priority system without resumption.

Control Room Plots. This system functions in much the same way as the Mk 113. It provides solutions to the range, speed, and course problem, using position reports from the passive sonars as inputs. This system may have more than two parallel channels, depending on the skill and dexterity of the plotters. Here again the conning officer decides which contacts are plotted and which ones are interrupted if necessary. The service time of the plotters may vary, depending on the confusion in the control room and the speed of the contact.

Conning Officer. As can be seen in Figure 2.2, the conning officer receives many different kinds of data and must make many different decisions. If he is considered a server, and the customers the decisions required of him, a queuing system is seen to exist. The inputs come from many sources, although the rates eventually depend on the number of contacts in the system. There is a priority scheme, which he decides, and the customers are served on a first-come, first-served basis. However, a higher priority unit can interrupt a lower one. Interrupted service is allowed to continue from where it stopped. The service time is usually very short, often instantaneous. Mathematical problems and data collection difficulties will be discussed in the final report.

IV. MEASURES OF EFFECTIVENESS

Queuing theory will be of little use as a tool in analyzing the ASW mission unless it can provide a means of obtaining measures of effectiveness that are difficult or impossible to obtain in other ways. This section lists several measures that queuing theory can provide. These measures are easily available only if the mathematical queuing models can be solved satisfactorily. There are two classes of effectiveness measures. One class deals in probabilities, the other in expected values. We will list some in each class.

PROBABILISTIC MEASURES

All of the measures in this class are probabilities conditioned on the number and type of contacts in the system. If we assign priorities where the higher the value the more time spent on a contact, we can measure how busy the system is by

D = weighted sum of targets and their priorities

$$D = a_1 c_1 + a_2 c_2 + \ldots a_n c_n$$

where a_i is the ith priority weight and c_i is the number of targets in that priority class.

MOE 1: Probability (miss a contact $|D$) = probability that a target in range for its characteristics (noise level, etc.) is not picked up before it leaves the area

MOE 2: Probability (miss a contact for time $t|D$), that is a target is not picked up until t time units after it was "available"

MOE 3: Probability (lose contact of priority; before complete classification $|D$).

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EXPECTED VALUE MEASURES

MOE 4: Expected number of contacts lost in a given time, given D to start with

MOE 5: Expected time to classify given D in system to start with

MOE 6: Expected number in a given class in the system at any time

MOE 7: Expected value of D.

MOE 8: Expected total time in system.

With valid data and a suitable model these expressions can be used to evaluate changes in the ASW system. The mathematical models needed to generate the measures are discussed in the next section.

V. ANALYSIS OF SYSTEM COMPONENTS

This section analyzes various aspects of the systems described in Section II, such as—What is the input process? How is classification performed? What kind of information is presented? How long does the process take? What priority scheme will be used? A fundamental understanding of these components is required before mathematical models can be developed in the final report.

THE ASW DETECTION/CLASSIFICATION PROBLEM IN THE OVERALL SYSTEM

The sonar operators aboard an SSN 637 class submarine have a well-defined problem—they must search for, detect, and classify sound contacts. When the number of contacts is small (0 to 5) this job is manageable in that all contacts probably receive the attention they deserve. They are investigated fully and classified with reasonable confidence. Their general mode of operation is to follow some search pattern and, upon detection of a contact, observe it for a period of time (from 4 to 15 minutes approximately). If classification cannot be made immediately, the position is noted and the search continues. If another contact is detected it too is observed and the sonar returns to search. Thus the sonar time is divided between investigation of contacts and searching. As a contact becomes more important the sonar spends more time investigating it, trying to determine its classification as accurately as possible. If a contact is classified hostile and a decision is made to localize, the sonar is very busy with that contact obtaining data that enable the localizing submarine to maneuver into the best firing position. If no contact becomes important (that is, possibly hostile), the sonars continue their search. As long as the number of contacts is small, there is ample time to search and investigate existing contacts. However, as the number of contacts increases, the time between successive looks at any one contact increases. Also, the time between

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searching sweeps increases, and hence the sonars may not be aware of all events. The information lost and the contacts missed or allowed to come closer without detection depend on the congestion in the system, i.e., the number and kind of other contacts. To fully appreciate the loss of information in this situation, consider the following description of information collection.

If a sonar is trained on a contact constantly, the information accumulated by the operator will eventually be sufficient for confident classification. This information is often obtained in spurts, as the contact changes course or speed or alters its noise signature by changing auxiliary modes. Each incident of this type adds to the pool of information the operator has. At some point in time after detection the information level will be such that he can classify the contact. If for any reason these "spurts" of information are missed, the time of classification is postponed. Thus, within certain limits, the more often the sonar can look at the contact the faster classification will be made. On the other hand, searching for new targets is an extremely important part of the mission; in fact it is often better to know of all the targets within a certain range and have none of them classified completely than to have a few of the targets completely classified while being ignorant of the rest.

As pointed out above, when a contact is classified as potentially hostile, a larger portion of the sonar attention is directed to it. This certainly degrades the search capability, but the impending attack is more important than a thorough search coverage. Most existing models of antisubmarine warfare begin with a simulation of detection based on the sonar equation with random environmental conditions. If a detection is made the classification process is treated as a simple box that delays the attack for some period of time with some probability. Then the attack is simulated in detail. This treatment of the classification process seems to ignore the very important problem outlined above in a multicontact environment. How can we be sure that the hostile ship or submarine is detected and classified if the sonars are cluttered with fishing boats, merchant ships, and friendly warships? The performance of the sonar detection/classification system under these conditions is studied in the following subsections.

THE NATURE OF INFORMATION AVAILABLE TO THE SONAR OPERATOR
FOR USE IN CLASSIFICATION

Contacts are made by detection of acoustic energy emitted by the vessel. They are classified on the basis of the particular form of that acoustic energy. Each ship has an acoustic signature, which is a combination of sound frequencies from its propulsion and auxiliary systems. When the signature of a contact is determined it is compared with a file of known signatures for various classes of ships, and if a match is made the job is done.

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Although this appears simple and straightforward, difficulties arise because of contact range and ocean conditions. It is possible that a noise level contact be made, but neither the BQQ-3 nor the operator's ears receive enough information to begin classification. In general, as range to the contact narrows the signals become stronger and more information is available. At a certain range the information available from the contact may be enough to permit classification. At any range less than this, classification is also highly likely—if the sonar is trained on the contact.

Thus far we have discussed the steady-state system of frequencies available when a vessel is underway. Transient sounds emitted by a vessel at random may also be means of classification. A sound that identifies a class of ship but is not emitted with any regularity, a hatch closing falls in this category. Such a spurt of information may be almost instantaneous, but if the sonar is trained on the target when it occurs, classification will be made. These spurts can be treated as random spikes superimposed on the information available at a steady rate.

THE CLASSIFICATION PROCESS

When a "noise level" contact is detected by a sonar operator the immediate goal is to classify the contact. Normally the contact is to be placed in one of the following classes: noise level; unknown; merchant; lightcraft; warship; submarine. It is assumed that friendly submarines will not be detected because of operating rules. The sonar operator will listen to the contact for a while and attempt to classify it based on his experience and/or the BQQ-3 display. A tentative classification may be made following these observations. The sonar will then continue searching and eventually return to the contact. At this point the contact may provide more data based on a change in range, course, or speed. The additional information, and that previously obtained, is stored in the operator's mind and compared with his experience. If no match is made further searching is conducted. It is possible that while the sonar is searching in other directions the contact will produce information that can help classify it. This information may be present when the sonar looks at the contact again. If it is such that now classification can be made, service ends. However, had the sonar been looking when the change was made, or shortly thereafter, the service would have been completed sooner. Thus we see that information is generated by the contact and this information is accumulated by the sonar operator—if he is looking in the right place at the right time. The information available to an observer is shown abstractly in Figure 5.1.

The figure shows two "spurts" of information generated by the contact, such as changing auxiliary equipment or closing hatches. If sonar happened to be looking in the interval (T_0, T_1) classification would have occurred then. Also, any looks after time T_0 would result in classification. Essentially we have a distribution of transients, of random intensity, superimposed on the steady information available from the contact. In general, this steady information rises

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until the closest point of approach and then begins to decline. Fluctuations in available information are caused by ocean conditions, but these do not decrease the information accumulated by the sonar operator.
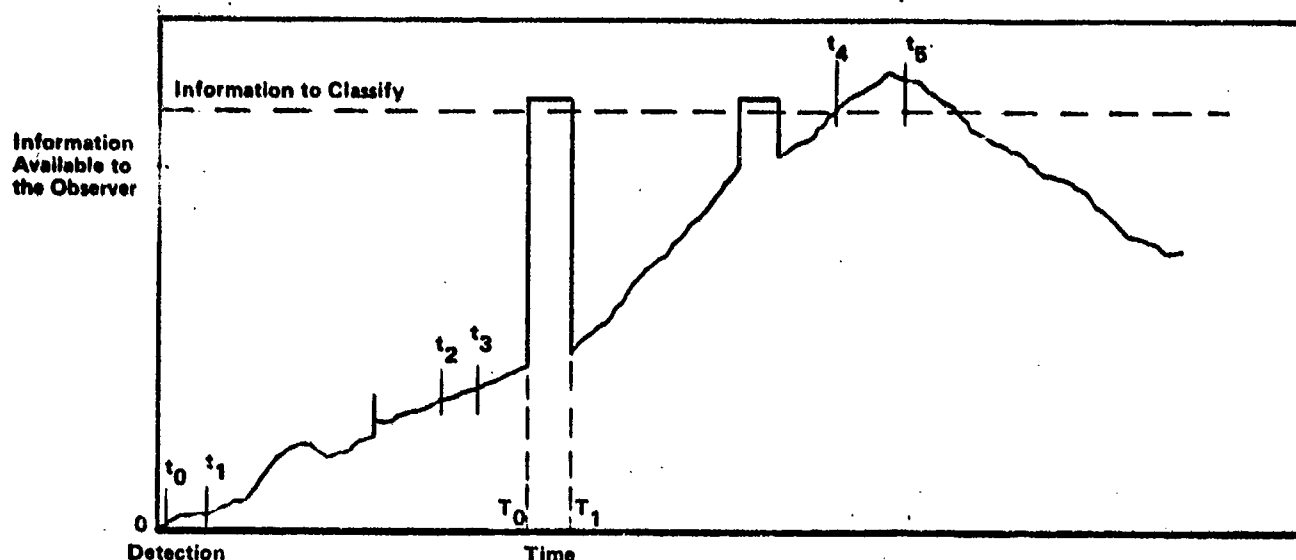

FIGURE 5.1. INFORMATION AVAILABLE TO AN OBSERVER

The accumulation of information is shown in Figure 5.2 for continuous observation. If the sonar only observed the contact during periods (t_0, t_1), (t_2, t_3) and (t_4, t_5), the accumulated information curve would look as shown in Figure 5.3. From these figures we see that the number of looks is not determined in advance. In fact, there is in a certain time range after detection in which classification would almost certainly occur in two looks. The trade-off is the chance of an earlier classification. Waiting too long for the second look would mean the contact had passed the closest point of approach and the data available would begin to decrease. If the service time of the contact is considered the time required to accumulate a given amount of information, we see in Figures 5.2 and 5.3 that this varies depending on the timing of the looks. Thus:

$$\sum_{i=1}^{\substack{\text{no. of looks} \\ \text{to classify}}} \text{length of look } i = \text{time to classify with continuous observation.}$$

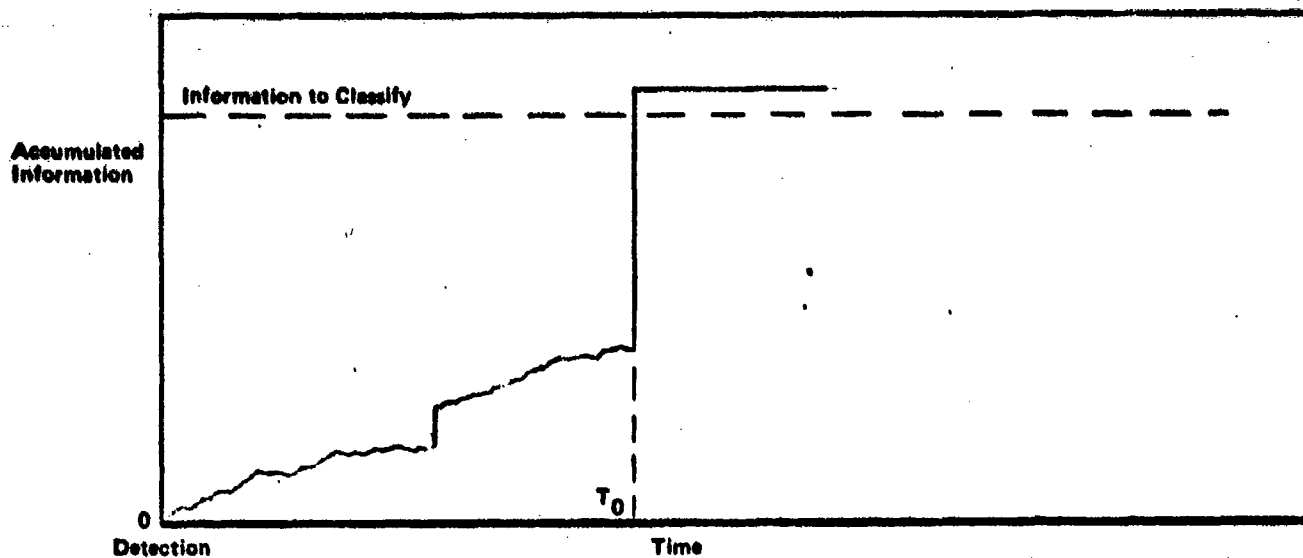It should be noted that the "number of looks to classify" is not unique.

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FIGURE 5.2. ACCUMULATED INFORMATION WITH
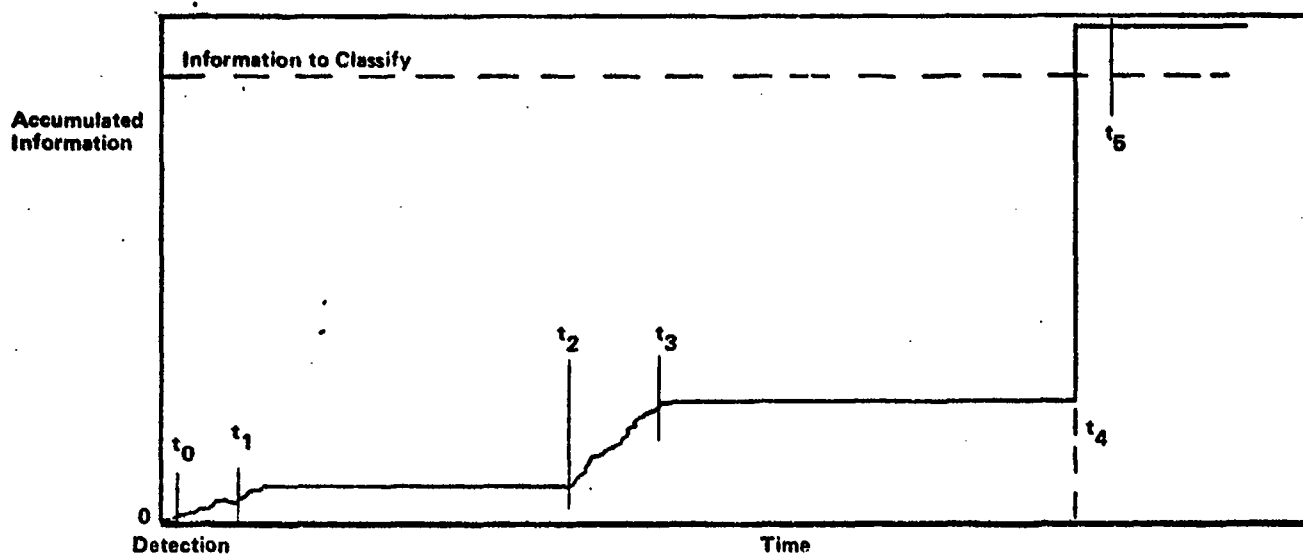CONTINUOUS OBSERVATION

FIGURE 5.3. ACCUMULATED INFORMATION WITH
INTERMITTENT OBSERVATION

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DESCRIPTION OF SERVICE COMPLETION TIME

The information available to the observing sonar from a contact as a function of time can be represented by a family of curves such as those shown in Figures 5.4, 5.5, and 5.6.
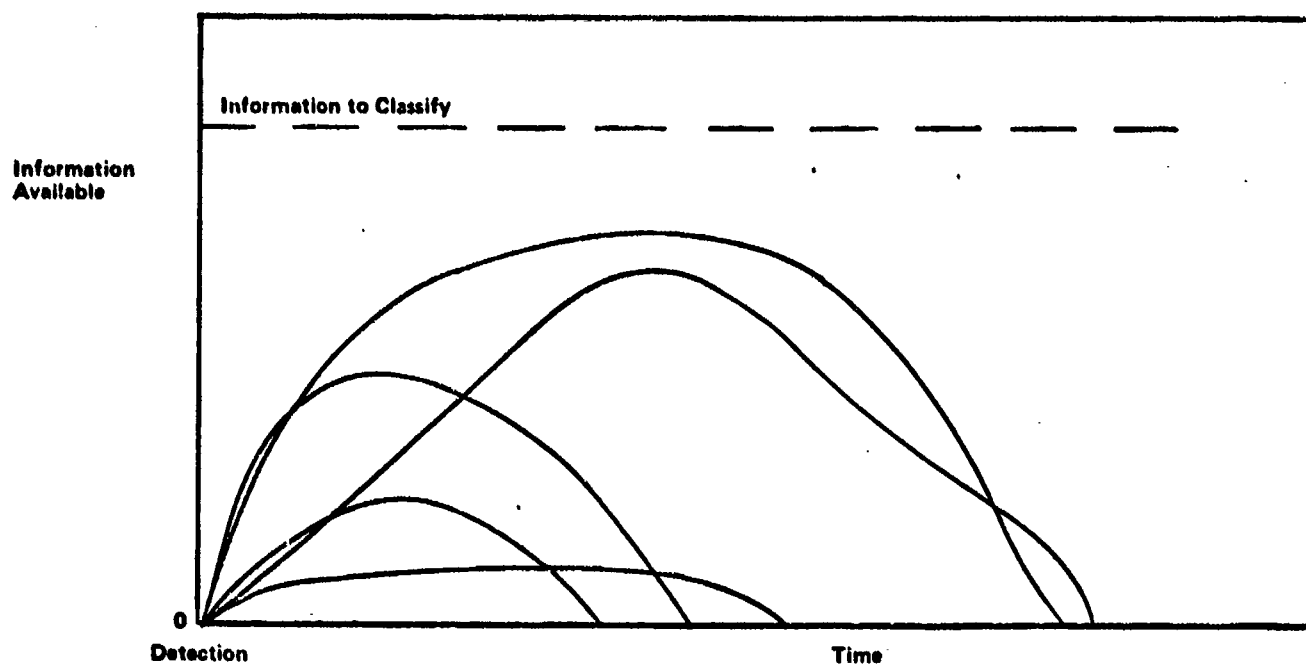
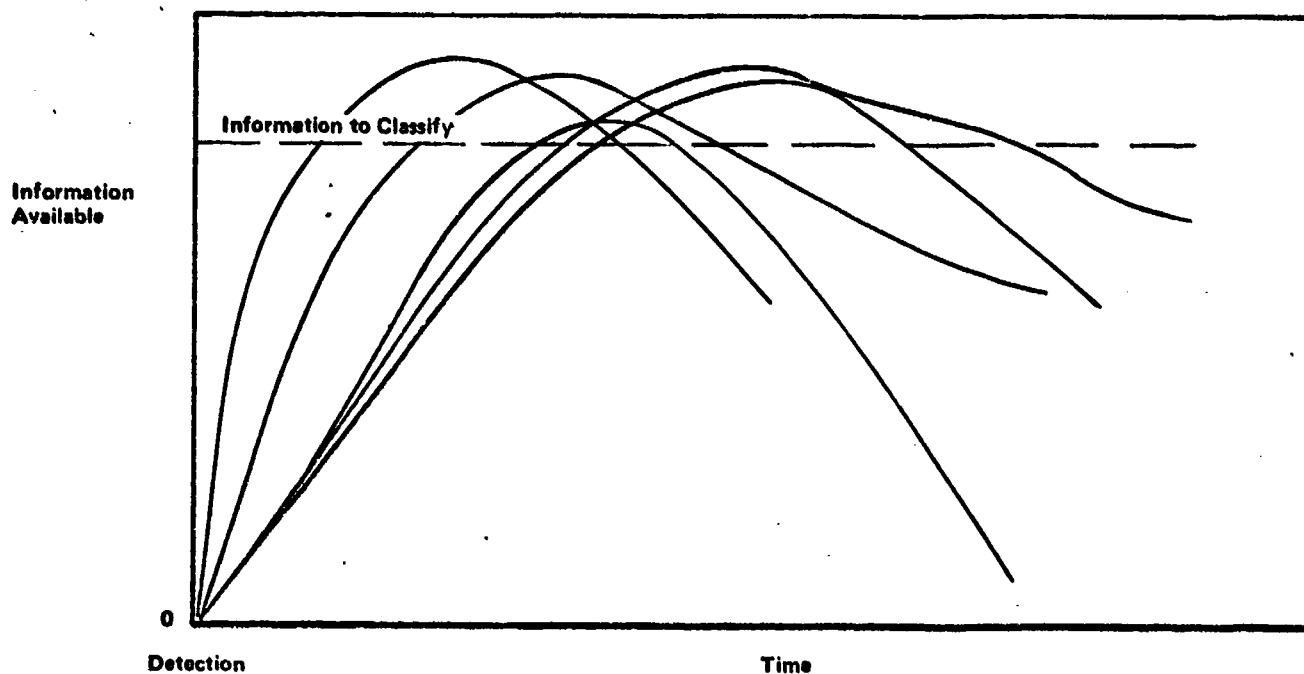FIGURE 5.4. INFORMATION AVAILABLE AS A FUNCTION
OF TIME-FRINGE CONTACTS

FIGURE 5.5. INFORMATION AVAILABLE AS A FUNCTION
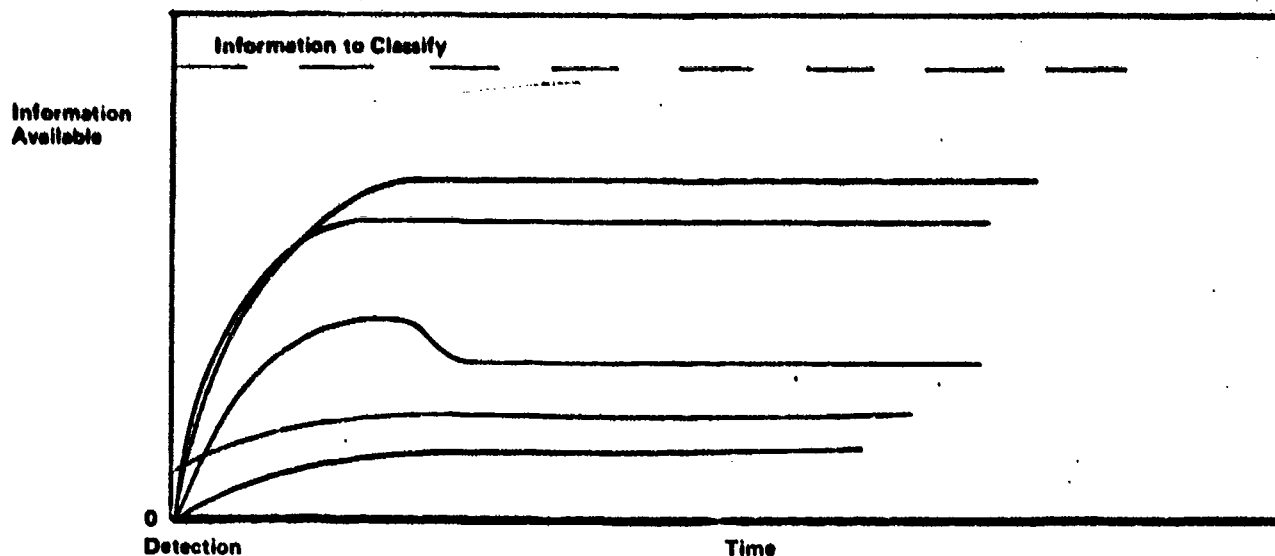OF TIME-APPROACHING CONTACTS

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FIGURE 5.6. INFORMATION AVAILABLE AS A FUNCTION
OF TIME-PARALLEL CONTACTS

The shape of the information curve is a function of many variables, such
as environment, range, sound intensity, and frequency. Certain contacts on
the fringes of the detection envelope may enter briefly and disappear. This accounts
for the curves shown in Figure 5.4. Other contacts approach the submarine with
different bearings and ranges. These are shown in Figure 5.5. Still other contacts
may approach and   y approximately parallel to the submarine. These contacts are
represented by Figure 5.6.

COMPUTER TIME-SP   ING AND THE ASW CLASSIFICATION PROBLEM

The customers in the ASW queuing system are the contacts to be
classified. These customers take on different priorities depending on their
present classification. A customer's priority can change after he has been
served because of the server's increased information. Since the server(s) must
look at all contacts and continue to search within some period of time, the
server's time is shared in much the same way as computer time is shared.
There is a fundamental difference however. In the computer case, a job is
completed after a given number of small service times (called quantums). Thus
if the job takes 10 minutes to run without interruption, five 2-minute quantums
are necessary to complete it. This is not the case in the ASW system.

In the ASW case, the time to classify the target is the service time. If we define T_C, a hypothetical service time for a particular target, as the time it would take to classify the target if it were observed continuously, then, as shown above, it is not necessarily true that the number of "looks," L, required to classify is $L = T_C/T_1$, where T_1 is the time per look or quantum. This is so because the contact is changing whether it is under observation or not. The fundamental difference between the ASW system and the computer time-sharing system is that the ASW customers are not static when the servers are busy elsewhere. The following paragraphs discuss the time required to complete service. Assuming for now that a contact approaches and is available for classification, suppose the available information curve is as shown in Figure 5.7.
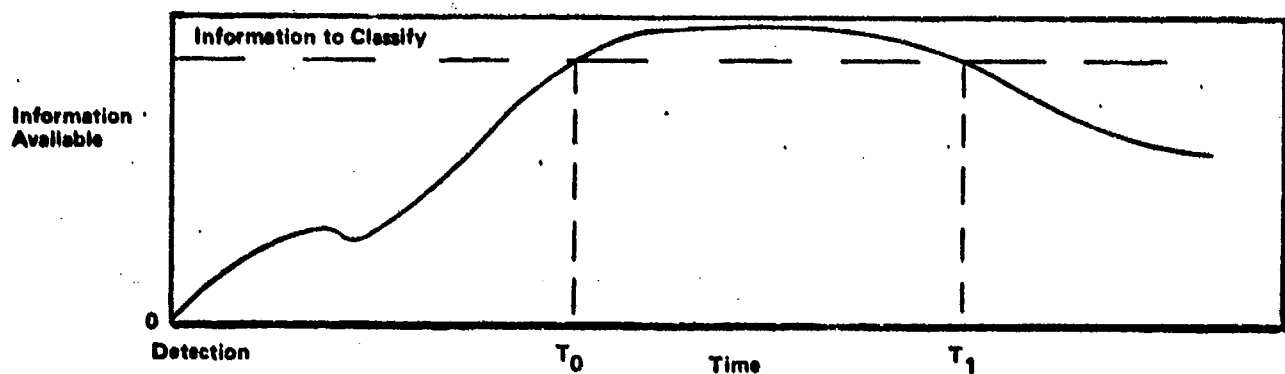

FIGURE 5.7. AVAILABLE INFORMATION CURVE FOR A CONTACT

Classification can occur only if the contact is observed sometime during the interval (T_0, T_1). Thus classification will occur during the interval $(T, T+L)$ with the probability below

Prob [classify during $(T, T+L)$] = Prob [look for L time units, starting at time T] x Prob [$(T, T+L)$ overlaps the interval (T_0, T_1)],

where L, the length of the observation, is a random variable that in part is a function of the contact's priority. With this formulation the major difficulty is determining the probability that a look will begin at time T, or in the interval $(T, T+\Delta T)$.

The time of the next look at a contact depends on the following variables: the number of other contacts in the system; their priorities; the priority of the contact under investigation; and the search doctrine. The relationships of these variables will be examined in the final report. It is now appropriate to discuss the priority scheme used in this system.

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Priority Scheme

The priority assigned to a contact reflects the sonar operator's estimation of its threat potential, based on the information obtained from previous observations. A priority may change based on the latest observation, e.g., what was thought to be a merchant ship, of relatively low priority, may be evaluated as a possible hostile warship after the next observation. Because changes can occur, the relative importance of a contact increases over time, starting from the end of an observation. Thus a possible merchant ship observed a long time ago might have higher priority than a possible warship observed more recently. This is an application of the delay dependent priority technique developed by Kleinrock.[1] However, it is complicated by the priority switching that additional information may cause. Priority switching can be modeled with a Markov switch matrix, where the P_{ij} element is the probability of switching from priority class i to priority class j after a completed look. The data required to develop this matrix are available from submarine logs. Data requirements will be discussed and further investigation of the time until next look presented in the final report.

ANALYSIS OF SUBSYSTEM QUEUES

The subsystem queues discussed in Section II are shown as separate queues, since they occur in the flow from a "noise level" contact to a completely classified contact (see flow diagram, Figure 2.2). However, since all of these queues use the same servers (the sonars), this system can be considered one large queue with several different classes of customers.

The classes are equivalent to the queue the customer is in:

1. No classification

2. Preliminarily classified

3. Determine range/speed, and course (Mk 113)

4. Determine range/speed, and course (plots)

5. Known range/speed, and course

6. Localize for information

7. Dormant.

Figure 5.8 illustrates this interpretation.

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[1] L. Kleinrock, "A Delay Dependent Queue Discipline," _Naval Research Logistic Quarterly_, Vol. II, No. 4, December 1964.
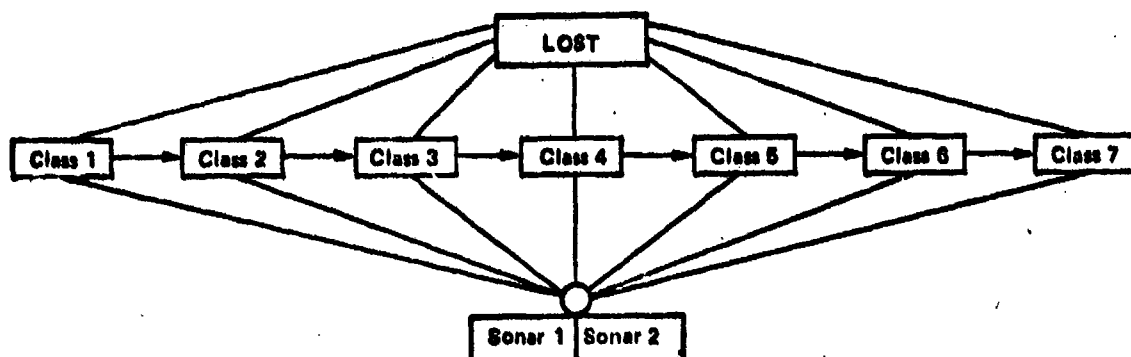
FIGURE 5.8. SINGLE QUEUE WITH SEVERAL CLASSES OF CUSTOMERS

Each class of contacts has inherent characteristics, which can be translated into some sort of priority scheme. As the investigation of a contact proceeds, the contact changes classes until it is completely classified or it is lost. This formulation of the detection/classification system leads to another analogy with computer time-sharing systems. The sonars can be thought of as parallel computers and the contacts as different types of programs. Normally customers in time-sharing systems do not change priority classes. Since they do in the detection/classification system, new methods may be needed.

In a formulation of this type care must be taken to account for all demands on the servers. An important role of the sonars has been ignored thus far—the search for new targets. This is the detection portion of the detection/ classification system. There is no immediate analogy with the computer system for this function. One approach is to treat the search function as another class of "customer" with an infinite service time. The priority of this customer depends on the other customers in the system. If this is defined as class 0, the system can be represented as in Figure 5.9.
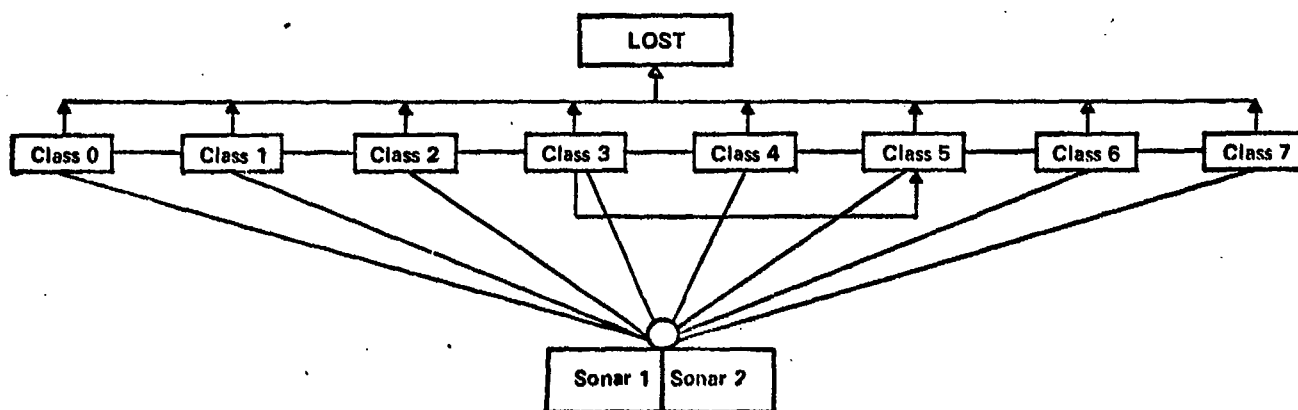

FIGURE 5.9. TIME-SHARING INTERPRETATION WITH
SEARCH FUNCTION INCLUDED

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Figures 2.2, 5.7, and 5.8, and the discussion above, imply that the contact must follow the path laid out from class 0 through class 7. In reality, an initial contact may be completely classified. This step may be taken from any point in the system. Similarly, other steps may be taken that skip one or two classes. Also, there is the possibility of feedback as discussed above with the localize-for-information queue. The possible paths to complete classification are shown in Figure 5.10.

Class	0	1	2	3	4	5	6	Lost
0		X	X	X	X	X	X	
1			X	X	X	X	X	X
2				X	X	X	X	X
3					X	X	X	X
4						X	X	X
5					X		X	X
6						X		X
Lost								X

FIGURE 5.10. POSSIBLE PATHS BETWEEN CLASSES

The transitions in Figure 5.10 suggest a possible Markov chain approach. In this case, however, the chain is not stationary. That is, the probability of moving from one class to another depends on the number of contacts in the system. Since this number changes with time, the transition probabilities change with time, contrary to the definition of a stationary Markov chain.

This discussion of the sonar queues has led to a system of time-shared sonars with several customer priority classes. The input to each class is determined by a class before it in the time sequence of events, with the input for the first class coming from an infinite population. This system will be treated mathematically in the final report.

CONCLUSION

This technical memorandum has presented a description of the ASW mission, its subsystems, and their information flows. It has analyzed certain problems in the classification of contacts with a view to applying queuing theory. It has demonstrated the application of a "time-shared system" approach to the sonar/contact processing system. The mathematics required to implement this approach will be investigated in future work.

Operations Research, Inc.

APPENDIX A
GLOSSARY OF STANDARD AND SPECIALIZED TERMS

ARRIVAL RATE—Number of customers arriving in a unit of time.

BALKING—Refusing to enter waiting-line.

CUSTOMER—In the ASW System this is the contact to be classified.

DYNAMIC ANALYSIS—Takes into account the effects of time on system performance.

MARKOV CHAIN APPROACH—Mathematical technique used to describe systems in which the next state of the system is influenced only by the present state.

NON-PREEMPTIVE PRIORITY—Service discipline in which an arriving unit of higher priority waits until the service of the current unit is completed.

PREEMPTIVE PRIORITY—Service discipline in which an arriving unit of higher priority can interrupt the service of a lower priority unit.

QUANTUM—Small unit of time used to describe the amount of service given to a customer in a time-shared system.

QUEUING THEORY—Mathematical theory of waiting-lines.

RENEGING—Leaving waiting-line before being served.

SERVER(s)—In the ASW System this is the passive sonar(s).

SERVICE DISCIPLINE—Manner in which customers in the waiting-line are chosen for service.

SERVICE RATE—Number of customers served in a unit of time.

SOUND VELOCITY PROFILE—Velocity of sound as a function of depth.

TIME-DEPENDENT PRIORITY—Service discipline in which a unit's priority is a function of the time it has been waiting.
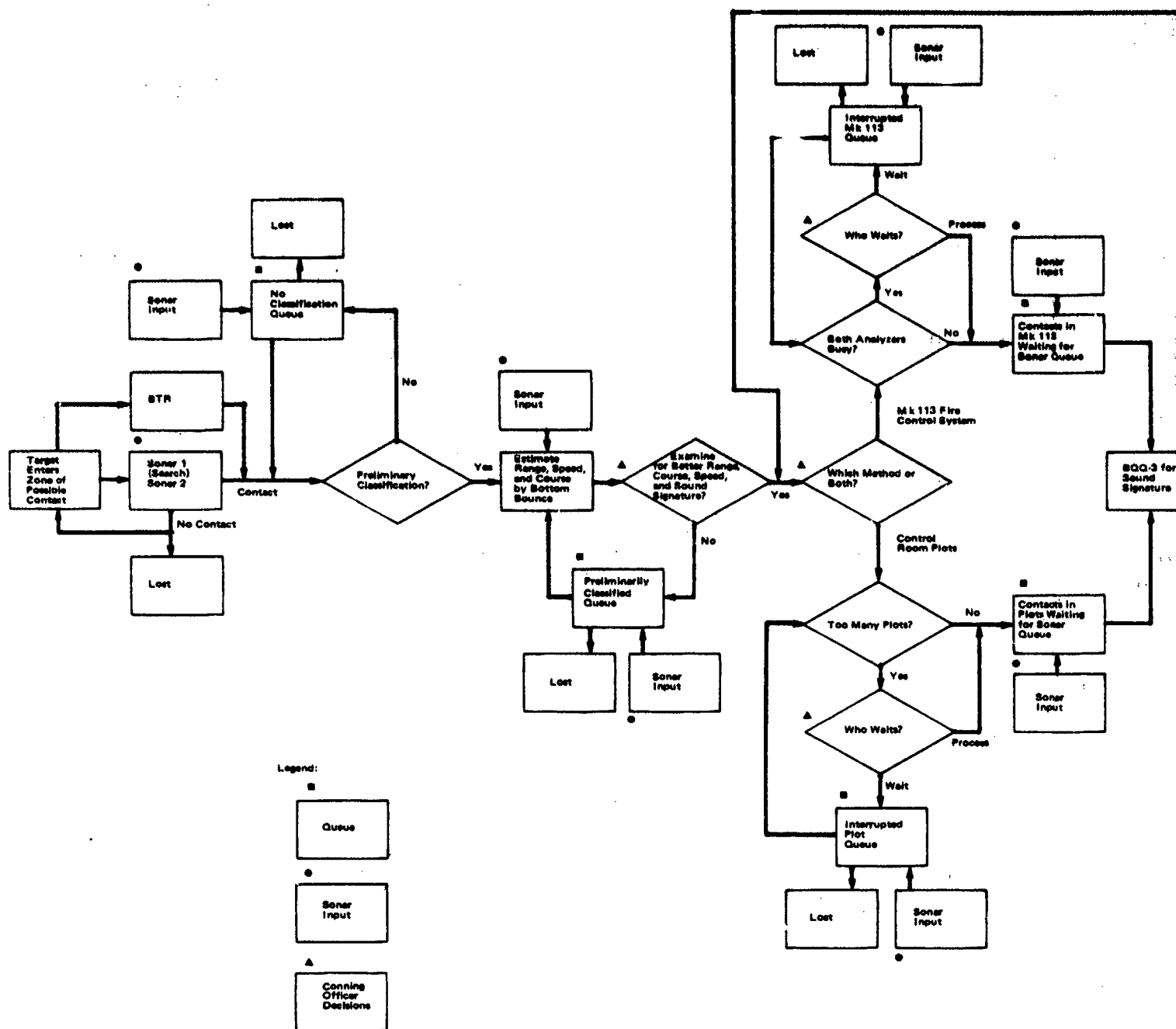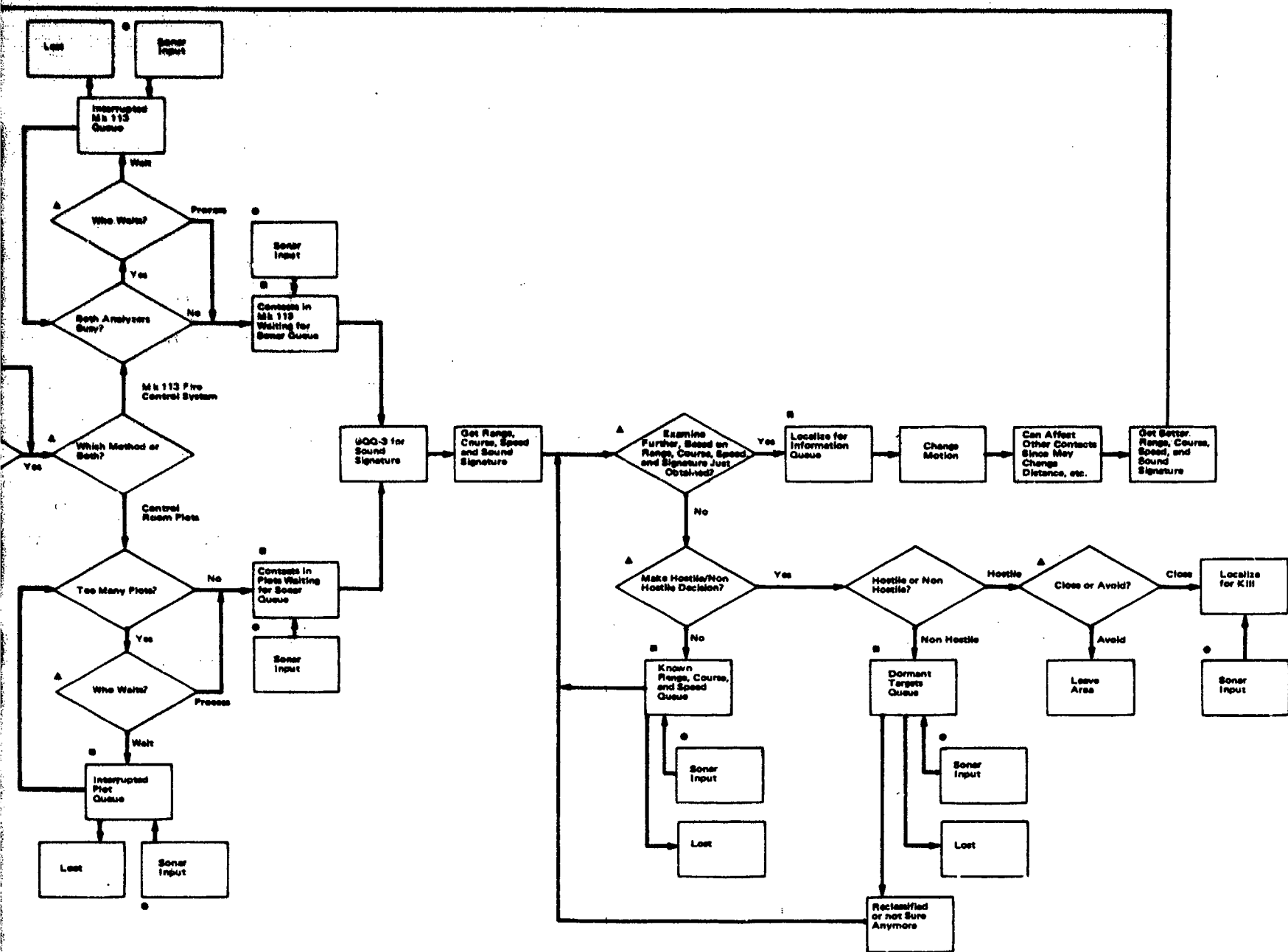
FIGURE 2.2. GENERAL FLOW DIAGRAM FOR
DETECTION/CLASSIFICATION/KILL IN
SSN 637 CLASS SUBMARINE
(INFORMATION AND DECISIONS)

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DIAGRAM FOR
KILL IN
NE
ONS)

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Distribution List.
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